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17**Analysis of structural behavior during collision event accounting for bow and side structure interaction**

Aditya Rio Prabowo a,b,∗, Dong Myung Bae c, Jung Min Sohn c, Ahmad Fauzan Zakki b, Bo Cao d, Qing Wang e a Interdisciplinary Program of Marine Convergence Design, Pukyong National University, Busan 48513,

32**Republic of Korea b Department of Naval Architecture,**

Diponegoro University, Tembalang, Semarang 50268, Central Java, Indonesia c

22**Department of Naval Architecture and Marine Systems Engineering, Pukyong National University, Busan** 48513, **Republic** of Korea d China Shipbuilding Industry Corporation Economic Research Center,

31Chaoyang District, Beijing 100012, People's Republic of China

e College of Shipbuilding Engineering, Harbin Engineering University, Heilongjiang, Harbin 150000,

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xxxx *This article belongs to the Solid Mechanics Keywords: Collision phenomenon Bow-side hull interaction Finite element analysis Internal energy Damage extent abstract The main goal of this study was to investigate the effects of selected ship collision parameter values on the characteristics of the absorbed energy in several ship collision scenarios. Non-linear simulations were performed using a finite element method (FEM) to obtain virtual experiment data. In the present research, the size of the side damage from a collision phenomenon were measured and used to verify the numerical configuration together with the calculation results using an empirical equation. Parameters in the external dynamics of a ship collision such as the location of the contact point and velocity of the striking ship were taken into consideration. The internal energy and deformation size on the side structure were discussed further in a comparative study. The effects of the selected parameters on several structural behaviors, namely energy, force, and damage extent were also observed and evaluated in this section. Stiffener on side hull was found to contribute significantly into resistance capability of the target ship against penetration of the striking bow. Remarkable force during penetration was observed to occur when inner shell was crushed as certain velocity was applied in the striking bow. © 2016 The Author(s). Published by Elsevier Ltd on behalf of

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8This is an open access article under the

CC BY license (http://creativecommons.org/ licenses/by/4.0/). In recent years, the demand of case investigation with objective to minimize the phenomenon of ocean pollution and vessel losses as the casualties of collisions and grounding has risen as the primary necessity. One example is the environmental damage caused by the Exxon Valdez accident, which forced the USA to make The Oil Pollution Act 1990 (OPA-90) into law. The accident of several roll on-roll off ships, such as the Scottish Viking on 2010, the Primula Seaways in 2015, and remarkable accident of collision between the Doña Paz and the MT Vector in 1987 with the casualties of more than 4000 lives, made the related parties perform investigation and evaluation of the safety of passenger ships in many countries. Collisions and groundings contribute significantly to ship structural damage. Based on the statistical data from the International Oil Pollution Compensation Fund in ∗ Corresponding author at: Interdisciplinary Program of Marine Convergence Design, Pukyong National University, Busan 48513, Republic of Korea. Fax: +82 515296608. E-mail address: aditya@pukyong.ac.kr (A.R. Prabowo). 2006, collisions and groundings were responsible for more than 50% of all environmental damage as cause of oil spill [1]. A collision accident also occurred in the Sunda Strait on May 3, 2014, at around 2:25 am local time, between Sumatra Island and Java Island which are both located in the Republic of Indonesia. The collision occurred between the Ro–Ro passenger ship Marisa Nusantara and the reefer Qi Hang. After the accident, the struck Ro–Ro passenger ship Marisa Nusantara, which carried 75 passengers and 47 vehicles, experienced severe damage at the forepeak hull side, with a tear 7 m in length and other material losses from passengers. This

10paper presents a comparative study on the results of

a simulation using several parameter values in collision simulations. Finite element (FE) simulations for several collision case scenarios were conducted to obtain virtual experiment data. This study was focused in assessing structural response as collision load was applied on target structure. Scenario was built based on several physical parameters which were classified as dynamic parameter in ship collision. Comparative analysis was conducted on each parameter category to obtain prediction of side structure behavior after collision event.

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8This is an open access article under the

CC BY license (http://creativecommons.org/licenses/by/4.0/). Fig. 1. Illustration of coordinate system. The studies by various methods on the object's behavior under collision load were performed by previous researchers and related parties. Research on the collision of tanker with double hulls [2] were performed including a comparative study in terms of struc- tural behavior of hull construction from bulk carriers in collision damage [3], and a finite element method (FEM) to the simulation of impact damage [4]. Other researches on impact technology were also carried out between 2011 until 2014 in terms of mathematical and virtual models [5–7]. The ship collision study by Wiśniewski and Kolakowski [8] de- scribed numerical simulation of simplified experiment on the im- pact phenomenon. Several simulations of ship collisions based on the collision type were studied by Haris and Amdahl [9]. Another reference on this subject is the study of Kitamura [10], in which he stated that in order to obtain good accuracy and practicality, the study must be based on several data, including from finite element analyses (numerical experiments), physical experiments, and ac- tual accidents. When a collision between ships occurs, the involved ships are classified as the "struck" and "striking " ship. The struck ship is the ship that has part of its body penetrated by the other ship. The striking ship is the ship that penetrates into the other ship. Col- lisions can occur in many possible scenarios, for an instance is side collision. In this phenomenon, the side part or hull of the struck ship is crashed into by the striking objects which can be ship, rigid log, etc. Simplified coordinate system used in the collision process is presented in Fig. 1. Collision analysis itself has experienced continuous improve- ments since it was first introduced by some researchers. The meth- ods used in collision analysis

10can be divided into four categories: empirical methods, simplified methods,

experimental methods, and FEM. Empirical methods have been introduced and developed by many researches. Minorsky [11], Woisin [12], and Zhang [13] were considered in the present study. Improvement on the methods of both Minorsky and Woisin was presented by Zhang. The proposed formula by Zhang repre- sents the damage in crushing, folding, and tearing categories. An FE approach is introduced these days for performing the anal- ysis and simulation of complicated cases in physics and math- ematics. The approach basically consists two different analysis concepts. The non-linear concept is performed to calculate the structural response, such as stresses and deformations during gen- eral loading and non-linear material conditions are defined in phenomenon model. The non-linear analysis generally involves complex model, in which high non-linearity is involved, but most Table 1 Configurations of struck ship. Characteristic Value Length over all (m) Length between perpendicular (m) Breadth molded (m) Design draft (m) Depth (m) Frame spacing (m) 85.92 78.00 15.00 4.30 10.40 0.60 Table 2 Configurations of striking ship. Characteristic Value Length over all (m) 144.50 Breadth molded (m) 19.80 Design draft (m) 5.60 Depth (m) 10.20 of complicated phenomenon, namely contact mechanics was successfully observed using this method. The implementation of a non-linear analysis was considered to be the most suitable for the present study. In this research, a non-linear FE analysis was conducted using the LS-DYNA FE codes to produce virtual experiment data. The algorithm in this code is characterized as given in Eqs. (1) and (2). {at} = {M}−1 ??Ftext? − ?Ftint?? , F int = ? ?? BTσndΩ + F hg ? + F contact, Ω (1) (2) w?Fhteextr?e i{satt}heisatphpeliaedcceexletreartnioalnaantdtibmodeyt,fo{Mrce} visecthtoer,m? aFstinst?miastrtihxe, internal force vector given by Eq. (4), F hg is the hourglass resistance force, and F contact is the contact force. In this algorithm, the velocities and displacements are then evaluated as presented in Eqs. (3)–(6). ?

6**Vt+?t/2? = ?Vt−?t/2? + {at}?tt,** (3) **{ut+?t} = {ut} + ?Vt+?t/2??tt+?t/2,**

(4)

27**?tt+?t/2** = 1 2 **(?tt +?tt+?t),** (5) **?tt−?t/** 2 = **(?tt −?tt+?t).**

1 2 (6) The model is progressing by adding the updated displacement variable to the initial model {x0}, as presented in Eqs. (7) and (8). {xt+?t} = {x0} + {ut+?t}, (7) λi+1 = λi + Kcont?xpenetr. (8) A collision occurred on May 3, 2014, between Sumatra and Java Island, specifically in the Sunda Strait, 5 km from Bakauheni Port (Lampung Province). Marisa Nusantara, a Ro–Ro passenger ship was severely damaged after Qi Hang, a reefer ship struck its hull. Qi Hang ran with a velocity approximately 6 m/s into the starboard side of the Ro–Ro passenger ship. As a result, a rip formed with a length approximately 7 m and width 5 m. An illustration of the damage can be seen in Fig. 2. The penetration depth was 2 m between the main deck and middle deck [14]. The configurations and main dimensions of these ships are presented in Tables 1 and 2, respectively. The struck ship is the ship that has its body penetrated by the other ship, whereas the striking ship is the ship that crashes into the other ship. In the FE experiment, the plastic-kinematic characteristic was implemented in the analyses, and material model for virtual experiment is given in Table 3. The numerical models of the both Fig. 2. Condition of the struck ship: (a) damage as ship arrived in shipyard and (b) repairing process. Fig. 3. Ships involved in collision accident process: (a) struck ship and (b) striking ship. of involved ships are presented in Fig. 3. Some researchers such as Kitamura explained that the strain failure is not constant but varies with the structural arrangement. In certain cases, the material failure characteristic is influenced by the structure size, shape, and loading mode, which causes the failure to be different in each sector [15]. The stress–strain field, which can be affected by the loading pattern and structure configuration also makes a contribution which is related to the material failure behavior [16]. However, for a ship collision analysis itself, Simonsen [17] men- tioned that the simplified analysis is built based on the overall deformation mechanism, so that the effort to trace the strain history at a very detailed level can be considered impossible. Therefore, several researchers such as Wang [18] and Paik and Pedersen [19] used the maximum strain failure in their studies. The maximum strain is defined as the condition when a struc- ture reaches the critical strain and the structure undergoes rup- ture. Based on their study, present research will also use maximum strain failure criteria in their studies, and showed that a structure ruptures when the maximum strain in it reaches a critical point. Amdahl and Kavlie [20] described that the mild steel has the tensile ductility characteristic in a range between 0.20 and 0.35. The latest implementation of this value was considered and applied by Ozguc et al. [3] when they were defining material model for collision anal- ysis. Based on a review of the previous literature and Ozguc's ma- terial model, this research applied the failure strain as presented in Table 3. The strain rate P represents the Cowper–Symonds con- stant. In this research, the applied value was recommended in the software package LS-DYNA library [21], while a friction coefficient for mild steels was considered [22]. The event of a collision was considered to be physical phe- nomenon that was virtually modeled and the calculation was per- formed by numerical method of FE approach to obtain

experiment results. The Belytschko–Tsay element was selected to be used on the ship model in the present research. The work of Alsos and Amdahl [23] and Prabowo et al. [24] indicated that the imple- mentation of element-length-to-thickness (ELT) ratio on models in numerical experiments should be in the range of ratio between 5 and 10 so that the stress and strain in specific area can be well ob- tained. The applied ratio for the involved models was in the range 8 and 10. Several collision scenarios were considered in the simu- lations and analyses. The results of a numerical experiment would be compared with the damage from the physical phenomenon and calculation results from empirical formula to verify the method used in the numerical simulation. The simulation used the non-linear FE while the details of the procedure for this study are presented in Fig. 5 A study to verify implemented setting and configuration in FE simulation would be conducted. Three denoted scenarios were used in this study to be analyzed and compared with calculation using energy formula and collision data. Location of contact points was predicted between main and middle deck as presented in Fig. 4. The striking bow was implemented with velocity 6.17 m/s and the struck ship was set to be fixed on centerline while the end of model was clamped. In terms of formula, energy was calculated by developed Mi- norsky's formula [11] which is presented in Eqs. (9) and (10). This formula was refined by Zhang [13] that the basic formula of Mi- norsky was expanded into several formulas accounting for defor- mation patterns. The mathematical equations of these formulas are presented in Eqs. (11)–(13). Collision data in other hand was taken directly by field survey on involved ship in collision. Measurements of damages length and width were performed and would be used as real-life comparative data of numerical results E = 47.2RT 32.7, + (9) RT = ? PN LN tN + ? PnLntn, (10) E = 0.77εcσ0RT, (11) E = 3.50(t/d)0.67σ0RT, (12) E = 3.21(t/l)0.6σ0RT, (13) where E is absorbed energy, RT is destroyed material volume for both struck and striking ship/resistance factor, PN is damage depth of striking ship, LN is damage length of striking ship, tN is damage thickness of striking ship, Pn is damage depth of struck ship, Ln is damage length of struck ship, tn is damage thickness of struck ship, from εc = 0.10 (= εf /0.32) where εf is the steel material ductility εc is the critical rupture strain of the material which is determined obtained in tensile test [25], σ0 is the flow stress of the material, t is average thickness of crushed plate, d is average width of the plates in the crushed cross-section, and l is critical tearing length. Verification in energy was performed using Zhang's empirical formula since the formula was developed based on previous energy equation-formula such as those of Minorsky [11], Woisin [12], and Vaughan [26]. The results of the FE calculations for three predicted collision cases and its comparison with the empirical formula and collision data are presented in Figs. 6 and 7, respectively. It can be seen in the result, the greatest difference in the present Fig. 4. Illustration of involved objects in collision: (a) contact points and (b) impact situation. Fig. 5. Procedure diagram of present research. Fig. 6. Energy magnitude by FE simulation and energy formula calculation. Table 3 Material model for various impact scenario simulations. Properties Symbol Value Density (kg · m3) Elastic

28**modulus (MPa) Poisson's ratio Yield stress (MPa) Strain rate**

sensitivity-I (s−1) Strain rate sensitivity-II (s−1) Failure strain ρ EX NUXY σys C P 7850 210 000 0.30 440 3200 5 0.20 analysis between the FE and formula calculation was 4.85%, which was smaller than the differences in the previous work of Ozguc et al. [3] for ship collisions, which showed difference values in range of 2.87%–72.82%. In terms of energy, we can conclude that all of the FEM results showed a good correlation with the formula calculation. The deformation size for three cases from numerical simulations and the damage characteristics from the direct measurement also showed positive agreement with the Fig. 7. Damage characteristic on side structure after simulation. Field data represents direct measurement. Fig. 8. Internal energy of impact location study: scenarios 1 and 2. most similar one to damage on repaired ship was the collision B. Therefore, the setting and configuration of the numerical simulation was successfully verified with the real collision data and formula calculation. The configuration and setting from this study would be used and applied in further analysis and calculation A virtual experiment with the verified method was performed using several selected parameters. A comparative study on the re- sults with various parameter values was conducted, and the results were presented. The collision location and ship velocity were the main focus in this study. Several simulation scenarios were conducted with the impact location on the struck ship as the independent variable to obtain information about the influence of the collision location on the simulation results. Six collision scenarios were utilized in the current study. The impact point locations were divided into two basic locations: frame numbers 115 and 117 for the main frame and web frame, respectively. The impact points for scenarios 1 and 2 were at the web and main frame. The targets for scenarios 3 and 4 were at the intersection between the main deck with the web frame and the main frame. On other hand, scenarios 5 and 6 were at the intersection between the middle deck with the web frame and the main frame. The obtained results during experiment process, indicated that the web frame had a better capability in resisting penetration of the striking ship than the main frame. The impact locations at the web Fig. 9. Internal energy of impact location study: scenarios 3 and 4. Fig. 10. Internal energy of impact location study: scenarios 5 and 6. frame and main frame, as well as the intersection, had the similar pattern for the internal energy, which led to this conclusion. The in- ternal energy values for each scenario are presented in Figs. 8–10. The amount of energy that was needed to plastically deform the target was varied in the range of 7%–28%. The intersection between the web frame and main deck, as well as between the web frame and middle deck, produced the largest amounts of energy dur- ing the collision process. During the collision of this scenario, the main deck and middle deck both acted as longitudinal structures and strengthened the side structure subjected to an impact load, together with the frame of the side structure. As can be seen in Figs. 11 and 12, when the intersection was subjected to an impact pressure, the pressure mainly occurred on the longitudinal mem- ber, which caused local pressure on this member. In a special car- rier or vessel with dangerous fuel such as a mother ship with a nuclear power plant, the hull structure of the ship is strengthened by transverse and longitudinal members to keep the plant safe and make sure the inner parts cannot be breached even if the ship ex- periences a collision load. In the external dynamics of a collision, the ship velocity is one of most influential parameters in relation to the analysis and calculation results. A virtual experiment was conducted to obtain information regarding how the ship velocity affects the structural response after collision. In experiments, the striking ship was moved to the designated contact point on the struck ship with five proposed velocity values. This configuration was already used Fig. 11. (Color online) Pressure contour after impact process: outer shell. Fig. 12. (Color online) Pressure contour after impact process: inner shell. and verified in the first part of this study. Five velocity values were proposed: 5, 10, 12, 15, and 20 knots or in metric unit were 2.57, 5.14, 6.17, 7.72, and 10.29 m/s. The five forms of internal energy-penetration are presented in Fig. 13. From these graphs, the velocity can be considered to have a significant effect during the collision process. As introduced in the velocity formula, for the same time period, the highest velocity will reach the farthest distance. In the study on the velocity influence, the contact point and other parameters used the same location and parameter. In this case, the velocity formula could be applied. As expected from the velocity formula, as the highest velocity, 10.29 m/s had the deepest penetration. With a striking ship velocity of 10.29 m/s, the penetration reached almost 4.50 m, which allowed the striking ship to penetrate the inner shell of the struck ship. Under this condition, both the struck ship and cargo, especially on the car deck, experienced remarkable damage as a result of the collision with the striking ship. This could also be verified using the force characteristic during the collision process in Fig. 14. The force behavior after a penetration of 3 m showed remarkable movement, which first occurred in the penetration Fig. 13. Internal energy for all proposed velocities. Fig. 14. (Color online) Force during collision process as advance penetration occurred. period of 3–3.5 m and gradually rose until reaching a peak with a value of approximately 23 MN, and decreased after the penetration passed 3.8 m. In this state, the inner shell was completely breached by the striking ship body and immense damage to both the ship and cargo could not be avoided. Starting from depth 4 m until the end of the collision process, the force tended to decline because there was no other structure after the inner shell was breached. The results of a comparative study of the influence of ship collision parameters were presented in this paper. The collision analysis successfully investigated various impact scenarios using verified configuration and setting in FE simulation. These config- urations and settings were applied in a comparative study which concerned two parameters, namely location and velocity. The re- sults from a location study indicated that the structure at the area of intersection between the main deck and web frame provided better resistance during the collision process than other proposed locations. It could also be concluded that the web frame at the side shell as well as at the intersection had a better ability in terms of strengthening the side structure than the main frame. In a ve- locity study, a higher velocity value also produced a deeper pene- tration and remarkable damage. A striking ship with a velocity of 10.29 m/s succeeded in penetrating the inner shell, which meant the destruction of the cargo on the car deck was unavoidable, with grave danger to the ship and passengers. A study of the stability and residual ship strength under this condition could be considered to be research topic for further study. Acknowledgments This work is successfully performed and finished with the grant from BK21 plus MADEC Human Research Development Group, Republic of Korea. 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